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DEVELOPMENT AND TESTING OF A 50-kA, PULSED SUPERCONDUCTING CABLE*

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Abstract

Prototype cables for 7.5-T, pulsed field application in tokamak poloidal field coils have been designed, fabricated, and evaluated. Successful fabrication of a 10 m superconducting sample represents the largest superconducting cable ever made. Details of the fabrication, the problems expected and encountered, and the solutions to those problems are discussed. Results of stability measurements on the superconducting prototype also are presented.

Introduction

High current superconducting cables will be required for the central solenoid and equilibrium field coils of future tokamak reactors. Present designs require currents of at least 50 kA in fields as high as 8 T and in addition, the ability to support current changes of up to 20 kA/s without performance degradation. A program to develop a cable to meet these requirements was established at the Los Alamos National Laboratory as a part of a more comprehensive program to design, develop, and test a central solenoid 20 MJ, prototype coil. The coil was to have a maximum field of 7.5 T and be capable of a complete field reversal in 2 s. Westinghouse (W) was under contract to Los Alamos to design and build the coil. Intermagnetics General Corporation (IGC) was a subcontractor to W during the design phase and was responsible for conductor and cable design. The design parameters are listed in Table I. IGC was subsequently under contract to Los Alamos to fabricate the cable. Details of the coil and cable design have been discussed elsewhere.[1,2]

The cryostable, 50 kA cable required for the coil is significantly larger than any superconducting cable designed or built to this time. Two prototype cables were fabricated by IGC under contract to Los Alamos. The first prototype was 20 m long, 10 m of dummy copper strands, and 10 m of cable with superconducting strands (Fig. 1). The second prototype was about 120 m of cable with copper strands. The 740 m of actual cable for the 20 MJ coil was not fabricated. The program was canceled prematurely due to changes in technical priorities in fusion development.

Previous work on high current cables for pulsed coil applications has been done. The first 50 kA cable was built for Los / Magnetics Corporation of America at New ectric Wire. Ten meters of superconducting c fabricated as a very preliminary atten, ;sess basic manufacturing ability and the severit problems to be faced. The effort successfully supported the fundamental design of a flat cable of subcables around a center strap. Results of this work have been presented.[3] The Japanese have designed two 50 kA cables as a part of their tokamak poloidal field program but have not yet fabricated or tested any prototype 50 kA ables.[4]

The manufacturing experience and problems associated with building the cable are discussed here. The discussion indicates the difficulty of the job to be done, the significant accomplishments achieved, and the need for further development. Results of performance tests on the prototype cable are presented.

TABLE I

STRAND DESCRIPTION

Radius	1.02 mm
CuNi.Cu:NbTi	0.7:5.2:1
Number of NbTi Filaments	1356
Filament Diameter	22.1 μm

SUBCABLE DESCRIPTION

Configuration	6 strands around core
Subcable Diameter	0.637 cm
Pitch Length	4.67 cm
Core Strand Material	Copper-Nickel

CABLE DESCRIPTION

Dimensions	1.532 cm × 12.480 cm
Number of Subcables	36
Mandrel Material	Nitronic 40
Mandrel Dimensions (uninsulated)	0.211 cm × 11.164 cm
Pitch Angle	18°
Operating Current	50 kA
I_{op}/I_c at 4.5 K, 7.5 T	0.71

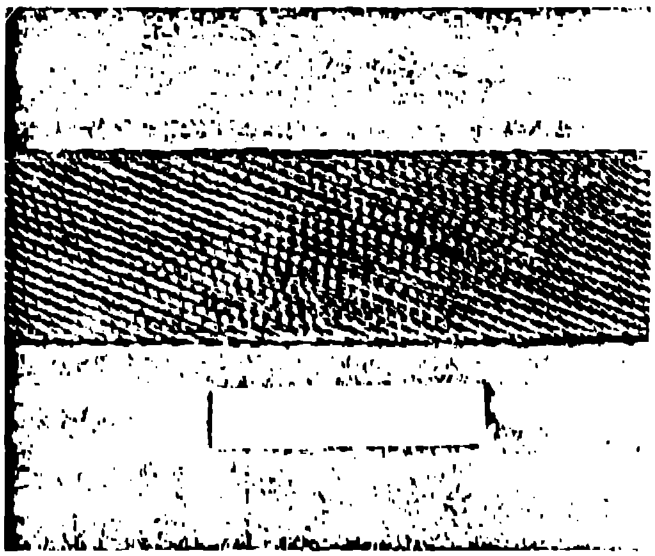

Fig. 1. Prototype 50 kA superconducting cable.

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Development

Cabling of superconducting strands as a means of achieving increased current carrying capability while at the same time providing improved stability and reduced losses is standard practice. Fabricating a 50 kA cable, one approximately ten times larger than any previously manufactured, is not standard practice and required an assessment of new and unique problems that might be encountered. The assessment led to general and specific concerns. The general concerns were:

1. Was there equipment capable of making large, flat cable, not a standard product in the wire and cable industry?
2. If so, would the equipment be capable of handling a cable of this size?
3. If such equipment existed, would it be available for use?
4. Would the cable be mechanically stable; could it be handled?
5. Was the design viable from a performance sense?

The specific concerns were:

1. The relative twist direction of the subcables and final cable.
2. The pitch length.
3. Insulation abrasion.
4. Subcable crossovers.
5. Applying and protecting insulation on the mandrel.
6. Inherent twist of cable.
7. Cutting the cable and changing take-up spools.
8. Correct subcable compaction and its measurement.
9. Other unforeseen problems.

To develop the technology and expertise to resolve the potential problems listed required fabricating one or more prototype cables. Phase one was to fabricate a relatively short, 20 to 25 m, prototype cable, half of which would be made of dummy copper strands and half of superconducting strands. Four goals were established.

1. To evaluate the suitability of the cabling equipment.
2. To learn how to operate the tooling and to evaluate its flexibility and suitability (Fig. 2).
3. To identify which specific problems occurred and measures required to correct them.
4. To use the superconducting portion for performance evaluation of critical current and stability.

The cabling was to be done on a planetary cabler at a subcontractor to IGC. The machine was capable of handling 36 subcables and the quantity of material required for the cable for the 23 MJ coil. The cabler was normally used as an armoring machine for high voltage transmission lines. The tooling was designed and installed and operated by IGC.

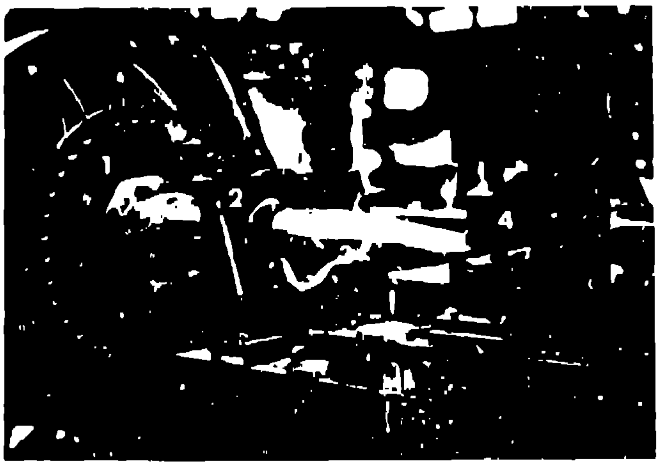

Fig. 2. Cable formation tooling showing spider guide (1), ring guide(2) (later removed), core pin(3), and rollers(4).

First Prototype Cable

Ten meters of dummy cable and 10 M of superconducting cable were successfully fabricated. The viability of the cable design and the essential performance of the equipment and tooling were demonstrated. Numerous specific problems, however, were encountered, including subcable crossovers, abrasion, cable twisting, pitch length, compaction, and overall handling. Problems not addressed included mandrel taping, cable cutting, cable protection, and twist handedness.

The major problem was subcable crossovers. To correct the problem, an external guide that tightly surrounded the cable was added during the run at the formation point between the core pin and the rollers (Fig. 3). Subsequently, no crossovers occurred; however, the tendency to do so persisted. Abrasion of the mandrel and strand insulations occurred, caused by worn guide dies in the cabler and by the tooling, because of inadequate adjustment capability. Twisting of the final cable was probably due to incorrect subcable pitch length. Initially the pitch length was set for 86 cm, which proved too long. This was shortened to 63 cm, closer to 56 cm, which had been calculated. Compaction, like all of these issues, was approached empirically. The assumption was made that maximum compaction within the constraint of no loss of strand or mandrel insulation integrity was optimal. Visual inspection and resistance checks made after completion of the cable indicated that the amount of compaction caused cut-through of the mandrel insulation. The cable was wrapped with heavy, nonadhesive tape and banded only about every meter, which was somewhat loose. This, along with its weight (~ 23 lbs/m), made handling without detriment very difficult.

The first prototype was fundamentally successful, as stated, in that it provided a length of superconducting cable to be tested, but it also exposed many problems and gave insight into the requirements to resolve them. Testing of methods to resolve these problems and other problems not addressed required that a second prototype cable be fabricated.

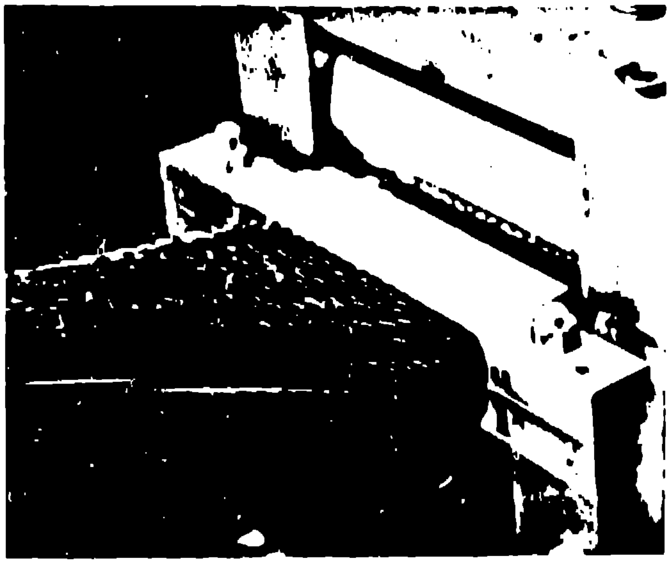

Fig. 3. External guide at cable formation point.

Second Prototype Cable

The materials used for manufacturing the cable were:

Mandrel - 304 stainless steel, full soft, 1/2 round edges, 11.143 cm wide × 0.211 cm thick.

Mandrel Insulation Tape - A polyester fiber, polyester mat with total thickness including adhesive of 0.019 cm and 5 cm wide.

Subcable Core - CuNi, 80/20 alloy, 0.216 cm dia., hard drawn, insulated with 0.025 mm thick GP-200 insulation (polyester-polyamide-imide).

Dummy Superconductor - Copper, ETP, 0.204 cm dia., hard drawn, insulated with 0.015 mm thick GP-200 insulation.

Cable Overwrap Tape - 7.6 cm wide, 0.28 cm thick glass mesh coated with glass mat and film to make glass non-irritating.

The general map of the cable was:

Footage	Description
0 to 111	Mandrel leader only - to attach to capstan
111 - 142	Cable startup
142 - 200	Average cable dimensions - 1.613 cm × 12.250 cm, pitch 20.5°
200 - 394	Dimensions changed to 1.651 cm × 12.390 cm
395 to 477	Pitch changed to 23°

The specific objectives of a second cable were defined as follows.

1. To fabricate a significantly longer cable to provide for adequate variation of parameters and to assure no new problems arising over an extended run.
2. To evaluate rebuilt cable formation tooling.
3. To evaluate reverse handedness between subcable and final cable in terms of cable formation and integrity.
4. To establish the mandrel taping operation and evaluate a new mandrel tape.
5. To evaluate overwrapping the final cable with paper tape both to protect it and maintain cable integrity.
6. To extend evaluation of pitch angle and compaction.
7. To evaluate effect of uniform subcable tensioning and level of tension on cable quality.

The only problems that were inherent over the complete run were related to the capstan. The shoe that guided the cable on the capstan was not designed to handle flat cables. The overwrap tended to catch and tear, and the cable tended to climb over itself from turn to turn. The shoe could be corrected; the overlap problem may require constant hands-on attention.

The core pin, outer guide, and rollers were all modified after the first prototype cable. The edge rollers were made adjustable, which effectively controlled edge compaction and eliminated mandrel insulation damage. Core pin modifications were made to reduce the possibility of subcable crossovers. They were not eliminated, but evaluation of the run concluded that other factors, discussed later, were of greater significance. Except for the occasional crossover, the tooling performed excellently.

The reverse in the twist direction from the subcables (left hand) to the final cable (right hand) gave a better overall lay to the final cable. The difference, however, was not great and could also have resulted from other factors, e.g., tooling or subcable tensioning. A final decision could be affected by other factors such as axial loading in the coil.

Mandrel taping, applied with a taping head, was done simultaneously with the cabling, but at the entrance to the bore tube. Two interlocking layers of tape were applied with each layer set for a 10 to 15% overlap and the interlocking overlaps staggered by 50%. To maintain the correct overlaps, frequent monitoring and adjustment were required. After taping, the mandrel went through a set of rollers. The only imperfection noted was an occasional small wrinkle as a bubble was rolled out. Evaluation of the tape integrity after cabling, showed it to be completely satisfactory; there was no cut through by strands from compaction on the flat face or on the edge. One significant problem did occur as a result of a deliberate action. A joint was made in both tapes at the same time and made overlapping rather than butt. This, together with the fact that spiral overlaps were on the leading edge, caused the tape to catch and drag on the inside of the core pin. The tape finally broke loose and bound up the mandrel in the core pin.

After formation and compaction, the cable was overwrapped with non-adhesive glass tape in two interlocking layers, each with a slight overlap and a 50% separation between tape overlaps. The tape was damaged at a number of points during the operation. The shoe and the capstan have been mentioned. The major damage to the wrap and possibly the strands occurred at the take-up spool, which had not been properly installed by the cabling company. A set of travelling rollers used to guide the cable onto the take-up spool or periodically improved and exacerbated the problem. The result was intermittent damage to the paper wrap over the whole length of cable.

Design requirements of the 20 MJ coil required a cable twist pitch angle of 18 ± 2°. Calculation of the correct pitch angle based upon dimensional parameters gave 23° to 25°; however, this is highly sensitive to small variations in certain parameter values. This sensitivity leads to uncertainty in the optimal pitch angle and the acceptable tolerance. Two different pitch lengths were used during the cable fabrication. Various constraints prevented trying more options. The pitch length was first set to 67.1 cm, which resulted in a pitch angle of about 20.8° ± 0.2°, close to the design criteria. There were gaps between subcables that were not uniform and ranged up to about 0.040 in. Roughly 90 m of cable were run. The pitch length was then set to 61.0 cm, which resulted in a pitch angle of about 23° ± 0.2°. The gaps between subcables became smaller but did not vanish. Overall appearance of the cable improved. The lay of the subcables around the cable edge now showed no bunching. The overall behavior (flow, spacing, lay) of the subcables at the forming point was improved.

No attempt was made on the first prototype to set tensions on the subcable payoff spools. On the second prototype the tensions were initially set to roughly 15 lbs, which appeared quite low because of the looseness in the subcables around the edge of the core pin. Nevertheless, 15 m of cable were run with no subcable crossovers. The payoff spool tensions were then increased to attempt to improve the looseness. The amount of the increase could not be measured. At the same time the cabling rate was increased from about 1 m/min to about 1.6 m/min. Subsequently, a number of subcable crossovers occurred. Reducing the speed and then the tension back to their original values reduced but did not eliminate the problem.

The second prototype demonstrated satisfactorily most aspects of producing a 50 kA cable. It did not resolve all potential problems, nor did it demonstrate that production level capability without constant hands-on attention had been achieved. Further improvements and changes are recommended.

The problem of torn overwrap can be corrected by assuring proper alignment of the take-up system, lining the inner sides of the take-up spools, and improving the flexibility and control of the guide rollers between the capstan and the take-up spool. The overlap problem on the capstan can presumably be corrected with the addition of an idler wheel. A linear capstan would be the best solution but would involve a major modification to the existing equipment.

Two major problems still exist with respect to the tooling. One is crossovers; the other is mandrel insulation binding in the core pin. Even with properly made tape joints, the possibility of the tape hanging up in the core pin exists; and if it did, the result would be catastrophic and irreversible. To eliminate this possibility, the mandrel taping must be done separately in a preliminary run. This would do two things. First, if a hang-up occurred, it could be corrected without the problem of cable damage. Second, after taping, spooling, and refeeding into the machine, the mandrel would then have the tape overlap on the trailing edge.

Various possibilities exist as sources of the crossover problem. One is that there is some minimum clearing time for the subcables to go around the edge of the core pin. If the cabling rate is too fast, the subcables may not clear and a crossover results. Another is that after a stop point, at startup, payoff spool tensioning may be nonuniform and initiate a crossover. To bring the possibility of crossovers to zero various steps should be taken. First, the guide piece and roller set-up should be mounted on the support table with screw adjustments to allow easy lateral, vertical, and rotational movement. The large torques from the subcables on the core pin cause major alignment problems. Second, another smaller spider or eye guide should be added and mounted between the existing spider and the cable forming point. The closer to the end of the core pin that the subcables are locked into place, the more difficult it is for crossovers to occur. Third, additional prototype cabling must be done to evaluate these changes and to identify further the allowed tolerances in operating parameters.

A couple of nontechnical factors pertinent to developing a 50 kA cable should be mentioned. The problems of working on equipment not specifically designed for the project at hand at a facility that is only nominally interested in the effort are considerable. Scheduling, availability, personnel, equipment cleanliness and reliability, and costs are all negative factors in doing development work of this type. There is, however, no alternative, only the recognition of the difficulty and the uncertainty of the impact of the factors.

Implications for Future Work

Future large scale tokamaks utilizing superconducting poloidal field magnets may require 30 km or more of 50 kA cable. Production scale-up to that quantity will be formidable. The biggest challenge will be to reach a level of production capability significantly more routine than now. Automated continuous monitoring of control parameters will be required to reduce the uncertainty of human control and attention now required.

The present cable design is the largest that could be accommodated on the equipment now used. There may be other facilities that could accommodate higher current, larger size cable designs. Tokamak designers, however, need to be aware of these limitations.

Testing of Prototype Cable

Stability measurements were made on the single strand, the six-around-one subcable alone, and the subcable within the final cable. Results for the single strand and the subcable alone have been previously presented.[5]

Full cable measurements were made on a 3 turn test coil (Fig. 4) at the Lawrence Livermore National Laboratory (LLNL) high field test facility. The test coil was assembled with the 10 m superconducting section from the first prototype test cable. To simulate the operating environment of the 20 MJ coil, the turn-to-turn insulation was provided by G-10 slats, 0.158 cm by 0.635 cm wide with a 0.318 cm spacing. For support and installation, the spacers were made in a "railroad tie" configuration, glued to two "railroad track" strips of fiberglass roving.

No 50 to 100 kA power supply was available at LLNL to power the full cable. It was, therefore, necessary to connect all the subcables in series by soldering together adjacent pairs at each end of the test coil. The net result was a 650 m long test length of subcable wound bifilarly in the full cable configuration. Current flowed in all subcables, but in alternate directions for adjacent subcables. This test method had the resulting advantage of eliminating any transformer coupling between the test coil and the background coil and hence the inherent safety and protection controls that would have been required.

Stability measurements were performed on the center turn of the test coil. Thin film resistance heaters, 0.655 m wide by 5.1 cm long were wrapped around numerous subcables. Voltage taps were placed on the six superconducting strands at about 10 cm intervals along the subcables. The stability measurements were made by inducing a normal zone in the subcable with the heater and then monitoring its subsequent growth or decay. Tests were done on various subcables at different relative locations within the full cable. In some tests three or four adjacent subcables were driven normal simultaneously. The

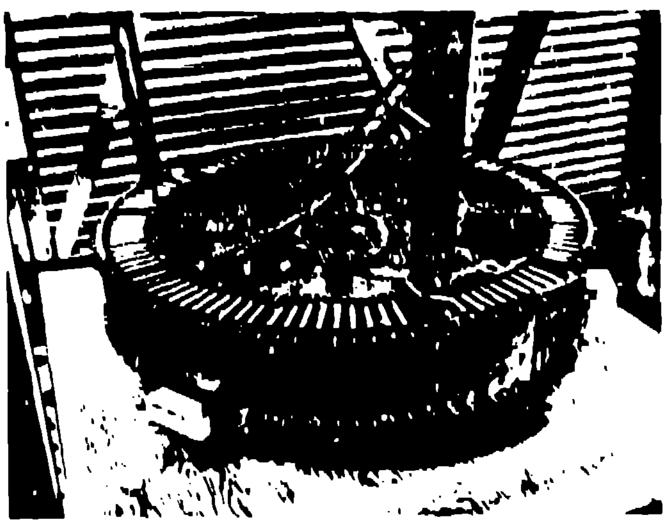

Fig. 4. Three turn test coil for stability measurements.

results were independent of subcable location and number normalized. Figure 5 shows the results of the subcable recovery current for these tests along with results for the subcable test alone in a completely open environment. Recovery current is defined here as the maximum current at which a normal zone, established with the minimum heater power required, will recover. Earlier measurements on single strands had established a surface heat transfer rate of approximately 0.5 W/cm^2 at 5 T. Measurements on a six-around-one subcable alone, assuming no change in heat transfer rate, gave a reduction in recovery current commensurate with a 40% loss in available surface area for cooling upon cabling; slightly more than the theoretical minimum loss of 33%. The results of the subcable test in the full cable configuration show no degradation of recovery current compared to the single subcable results. Because no change in heat transfer should occur, the conclusion is that the full cable configuration results in no further reduction of available cooling surface. Extrapolation of the results to the full cable give a cryostable limit of 65 kA, well above the criteria of 50 kA.

Qualifications to the results should be noted. Only one or a few subcables were driven normal in these tests. The 20 MJ coil specification required recovery from a half turn of the full cable being driven normal. Also the test coil had no top and bottom plate support structure. The effect of these two factors on the bubble dynamics and recovery current were to have been evaluated in tests on the actual coil. The support structure was felt to be nonsignificant.

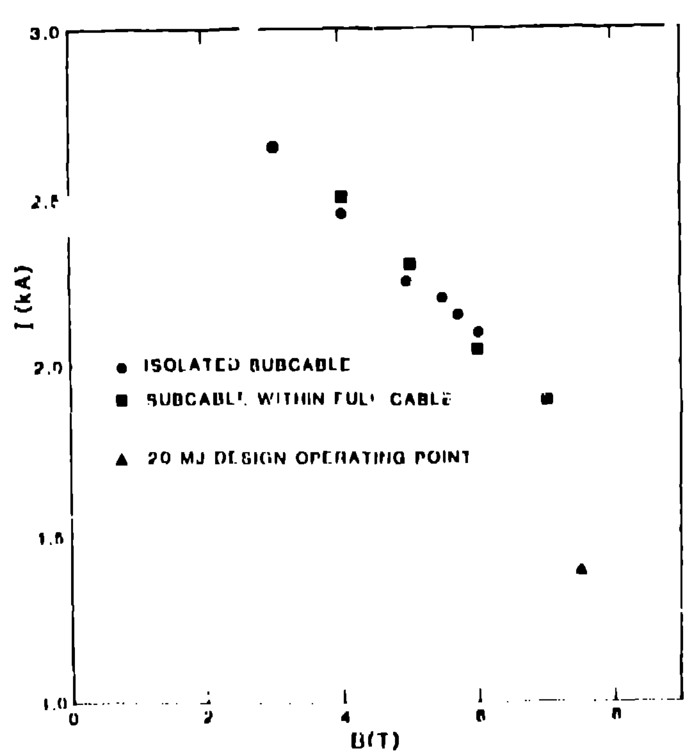

Fig. 5. Subcable recovery current as a function of field.

Conclusions

Prototype 50 kA dummy and superconducting cables suitable for high, pulsed field applications were successfully fabricated, evaluated, and tested. The size of the cable presented unique problems; most were resolved, others require further development. It is important to note that the uniqueness of the problems would not allow their resolution by technology transfer from other advanced programs such as METF and LCP. A continuing, separate effort is required to resolve the remaining problems and to reach the necessary level of automation for large scale production.

References

1. M. S. Walker, J. G. Declercq, B. A. Zeitlin, J. D. Scudiere, M. A. Janocko, S. K. Singh, E. A. Ibrahim, P. W. Eckels, J. D. Rogers, and J. J. Wollan, IEEE Trans., Mag 17, p. 908 (1981).

2. S. K. Singh, A. J. Jarabak, E. A. Ibrahim, J. B. Davis, P. C. Gaberson, J. D. Rogers, P. Thullen, and M. S. Walker, Proc. 9th Sym. on Eng. Prob. of Fus. Res., p. 644 (1981).

3. John J. Wollan, J. D. Rogers, B. A. Zeitlin, M. S. Walker, and T. A. deWinter, IEEE Trans., Mag 15, p. 816 (1979).

4. H. Tsuji, Y. Takahashi, K. Okuno, L. Dresner, E. Tada, T. Ando, R. S. Kensley, T. Ogasawara, K. Kuroda, T. Sato, T. Hamajima, S. S. Shimamoto, and K. Yasukochi Proc. 9th Sym. on Eng. Prob. of Fus. Res., p. 2035 (1981).

5. John J. Wollan, M. S. Walker, B. A. Zeitlin, D. A. Pollock, and S. S. Shen, IEEE Trans., Mag 17, p. 482 (1981).

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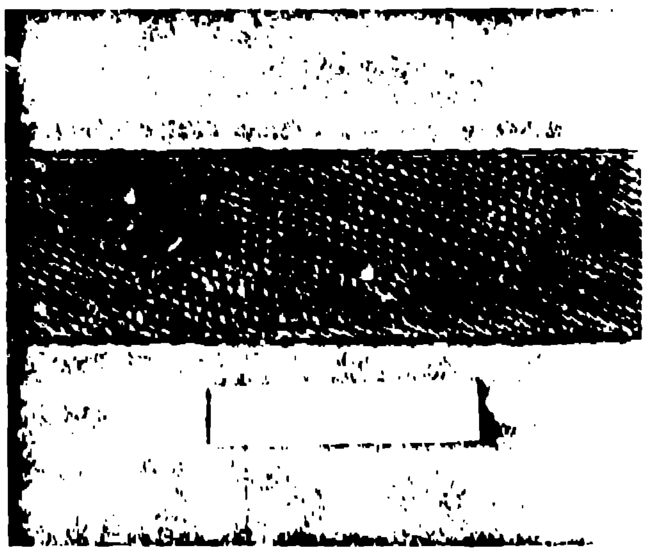

Fig. 1. Prototype 50 kA superconducting cable.

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